The impact of feed composition on the recovery of base metals in an electric furnace

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The smelting of platinum group metal (PGM)-containing ores in Southern Africa has undergone several changes due to changing concentrate blends resulting from the change in ore mined (from Merensky to the UG2, Great Dyke and Platreef ores). Maximising the recovery of base metals and PGMs in the matte phase of an electric furnace is integral to ensuring the sustainability of the business. Therefore, the focus of this research was to explore the relationship between the composition of the feed blend and the recovery of base metals. The composition of the furnace feed was quantified on a monthly basis through mass balance calculations from the Mortimer and Polokwane smelters (from 2012 to 2018) as well as from the Unki smelter (from 2018 to 2021). The recovery of base metals in the smelting operations was calculated using the feed and product compositions. The recovery data were compared to previously published recovery equations for non-ferrous metals in reductive oxide smelting. The recovery of the base metals shows an increasing nth-order relationship with the corresponding base metal feed composition. Models were developed to predict the recovery relationships, the relationship between the iron concentration in the concentrate and the base metal concentration, as well as the upgrade ratios of the base metals as a function of the base metal composition. The model was then used to determine the optimal operational region for a smelter based on the throughputs at each of the smelting operations, their design capacities, specific energy consumptions and assumed maintenance profiles.

INTRODUCTION

The platinum group metal (PGM) industry in South Africa has undergone a number of changes in operating parameters due to changes in the chemistry of the feed. The depletion of the Merensky reef has resulted in an increased need to mine the Platreef and UG2 reefs in South Africa, while in Zimbabwe, ore from the Great Dyke is mined, and the concentrate produced is smelted at the Unki smelter for Anglo American Platinum. Each of these reefs have characteristics which influence the smelting and converting operations and due to economic influences, Anglo American Platinum plans to optimise the mining of the Platreef, Great Dyke and UG2 reefs where it operates.

The purpose of this research was to comprehensively further the understanding of how blending of concentrates impact smelting recoveries. Some of the issues that needed resolution included determining the necessary changes required in the furnace operation and the energy required to smelt concentrate blends of different chemistries with greater efficiency. Challenges include the presence of chromite within the ore and subsequently the concentrate, the containment of slag and matte within the furnace due to the high temperature operation and the increased demand for energy efficiency in terms of cost savings and sustainability. Other challenges include the pollutants emitted by the smelters into the atmosphere, which may impact the environment.

The concentrate fed to PGM furnaces plays a significant role in the design, operation, control and planning of the entire PGM processing flowsheet. The factors that the concentrate influence include the selection and design of smelting techniques, energy efficiency, slag chemistry, matte chemistry and the further selection of downstream processing routes. Ultimately, the concentrate chemistry dictates what smelting process should be used and how the process should be managed, but its secondary effects lie in downstream processes where the products of the smelting operations play a role.

The recovery of valuable products plays a role within PGM processing. Increased entrainment of gangue materials during the concentrating step can result in recovery and processing issues within the smelting and converting steps. The overall recovery in the traditional PGM industry is constrained by the concentrators, which can vary between 80% to 90%.

LITERATURE

PGM Ore Reserves

The PGM industry across the world derives its valuable metals from a variety of sources of ores either primarily from the Bushveld Igneous Complex, South Africa (Merensky, UG2 and Platreef reefs), Great Dyke (Zimbabwe) or J-M reef (USA) or secondarily through nickel and copper ores (Gunn, 2009). Each of the concentrates stemming from the ores have various characteristics which require them to be handled differently in the smelting step. The Merensky concentrate was the concentrate of choice for decades in South Africa, prior to its depletion. The Merensky ore reserves, in 2021, accounted for 0.4% of Anglo American Platinum's ore reserves as opposed to the UG2 (17.4%), Platreef (78.8%) and the Main Sulfide Zone (3.4%) (Anglo American plc, 2021.)

Types of Concentrates in Southern Africa

Key differences exist between the different types of concentrate. The Merensky and Platreef concentrates contain lower Cr_2O_3 concentrations, lower oxide contents (silica, lime and magnesia) and higher base metal sulfide (nickel and copper) contents than the UG2 concentrate. The UG2 concentrate, however, has a significantly higher PGM content. When compared to the Merensky concentrate, the Platreef concentrate has comparable copper, nickel and sulfur contents to the upper range of the Merensky concentrates. The PGM content in the Platreef concentrate, however, is lower than in the other concentrates (Engelbrecht (2012); O'Connor and Alexandrova (2021)). The concentrate obtained from the Great Dyke has a high base metal content and low chromium content when compared to the typical Merensky and UG2 ores.

Mineralogy of the PGMs

PGMs rarely occur on their own but mostly as sulfides, tellurides, arsenides and alloys, often in association with base metal sulfides (Engelbrecht (2012); O'Connor and Alexandrova (2021)). As the PGMs are not necessarily associated with specific minerals in a solid solution with other phases, their concentration can also be affected through the size of the mineral grains. Knowing the manner in which PGMs are distributed within different minerals in an ore body is important for recovering the PGMs. Understanding the recovery of the base metal sulfides with which the PGMs are mainly associated, allows for a greater understanding of how to optimise PGM recovery (O'Connor and Alexandrova (2021); Oberthur (2011)).

Process description of PGM smelting operations

Smelting Operation

The smelting operations of various major PGM mining companies operate on similar principles, with the only differences being the equipment type or method of execution. Ultimately, most PGM primary smelters in South Africa, Zimbabwe and the USA have the same basic process. An example of a typical process is that of the Waterval smelter as described by Hundermark *et al.,* (2011), Figure 1. The concentrate melts within the furnace, during which the metal sulfide minerals separate from the gangue oxides, forming matte and slag respectively. The matte, containing mainly copper, iron, nickel and cobalt, acts as a collector for PGMs. The furnace matte is further processed in the Anglo converting process or in Peirce Smith converters or top blown rotary converters of other operators, where iron and sulfur are removed through oxidation described by Nelson *et al.,* (2018). PGM primary furnaces generally achieve high PGM recoveries with Lonmin Platinum (now Sibanye-Stillwater) recording higher than 95% in the smelting process due to high-temperature operation resulting in significant separation (Nell, 2004).

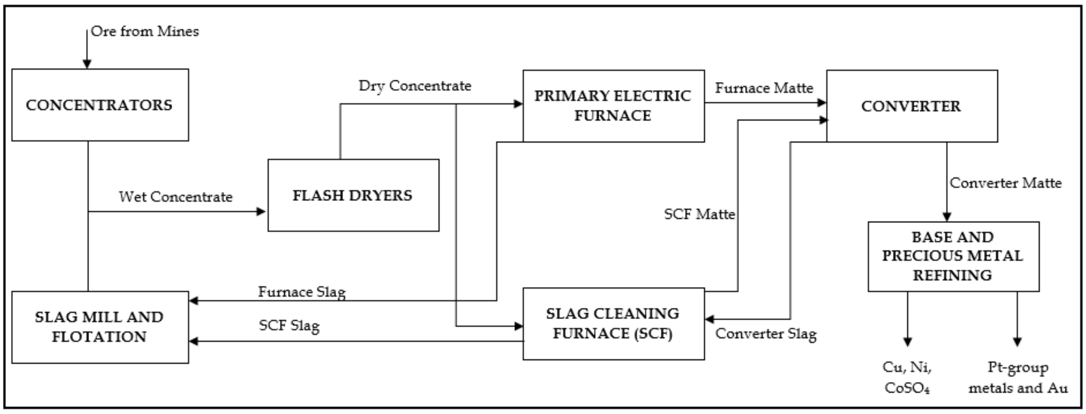

Figure 1. Waterval smelter block flow diagram (adapted from Hundermark et al.*, 2011).*

Mechanism of Matte Collection

The base metals and sulfide content of the concentrate determine the amount of matte formed, regardless of the PGM content. Upon feeding the concentrate into the furnace, the concentrate forms a bed or 'black top', which floats on top of the slag layer. According to Eksteen (2011) the base metal sulfides in the concentrate begin the process of partial desulfurisation when pentlandite ($Ni_9Fe_8S_{15}$) decomposes to FeS(s) and Ni_3S_2(s) at a temperature of approximately 650°C. Melting of the sulfides starts at 743°C with the decomposition of pyrite into pyrrhotite and liquid sulfur (Waldner and Pelton, 2005). At 1100°C the matte is completely molten. However, significant coalescence of sulfides in the black top only occurs after a substantial amount of liquid has formed in the silicate matrix. The liquid silicate serves as a pathway for the matte droplets through which they can coalesce and settle through the black top (Rivera Li Kao and Garbers-Craig, 2022). The matte droplets then move through the slag layer and collect at the bottom of the furnace, adding to the bulk matte layer.

The percentage of the mass of matte formed per tonne of concentrate is termed matte fall. Concentrates with a high sulfide content will result in a high matte fall. The maintenance schedules of the smelters are often centred on the amount of matte tapped. Thus, if there is an increase in the amount of matte tapped, there is a need for more maintenance and consequently reduced furnace availability.

Matte Entrainment in Slag

Physically entrapped matte droplets in furnace slag arise from sulfide phases in the feed (concentrate), fine dispersions of matte in regions of the furnace where large temperature gradients exist and matte particles carried into slag by gas bubbles rising through the slag-matte interface (Ip and Toguri, 1992).

Smelting recovery

Higher recoveries are indicative of processes that are more economically viable, more efficient and allow for a greater reduction of waste by ensuring the more effective extraction of valuable material. Mining companies thus need to understand the various levers that affect the recovery to remain competitive and enhance their portfolios. Nagaraj (2005) discusses some of the factors that influence material recovery, including but not limited to the type of feed, the mineralogy of the feed, the process flow, operating variables and the concentration of valuable materials within the feed.

The recovery of non-ferrous sulfide minerals from the concentrate to the matte phase decreases as the amount of iron oxidised and transferred to the slag increases (Grimsey, 2021). This was calculated according to the recovery equation which will hereafter be called Grimsey's model:

$$R_{Me} = \frac{1-y}{1-y+\frac{y}{K'_{Me}}} \qquad [1]$$

The recovery of the metal is represented by R_{Me}, y represents the fraction of iron reporting to the slag phase and K'_{Me} represents the distribution coefficient:

$$K'_{Me} = \frac{[Me\ pct](Fe\ pct)}{(Me\ pct)[Fe\ pct]} \qquad [2]$$

where *[Me pct]* and *(Me pct)* are the mass percentages of metal (Me = Ni, Cu, Co) in matte and slag respectively, while *[Fe pct]* and *(Fe pct)* are the corresponding mass percentages of iron.

This is indicative of the manner in which the sulfides are oxidised (Grimsey, 2021). Iron sulfide oxidises first and reports to the slag. The rest of the base metals do the same closer to the point where iron is fully oxidised. This results in a lower recovery of base metals and, as a result, the PGMs associated with the base metals.

Concentrate blending and flux addition

In an effort to mitigate the chromium effects of the UG2 concentrate and to minimise high matte falls of the Platreef and Unki concentrates, Anglo American Platinum (AAP) has employed the use of feed blending at its Polokwane and Mortimer smelter operations (Georgalli and Anderson, 2010). Blending is achieved through the mixing of Platreef and UG2 concentrates at specified percentages to ensure that a composite concentrate of pre-determined composition is fed to the furnace. In order to reduce the viscosity of the slag, lime was historically added to the concentrate Hundermark *et al.,* (2011). The addition of lime as a fluxing agent was discontinued by AAP and others to increase concentrate feeding capacity and decrease operating costs without any negative impact on the smelting operation in the presence of water-cooled sidewalls. In operations with non-cooled sidewalls, such as the Unki smelter, lime addition is still practised.

SAMPLING, DATA COLLECTION AND MODELLING METHODOLOGY

Data Sources and Collection

In order to obtain all the required inputs to determine the recovery and upgrade ratios of the base metals and precious metals within each operation, a site-wide mass balance was performed. This was completed across Mortimer smelter, Polokwane smelter and Unki smelter by the site personnel. The input was determined by weighing the amount of each type of concentrate entering the site along with sampling the concentrate to determine its chemical composition. The output was determined by weighing the amount of matte and slag leaving the site along with sampling of the matte and slag to determine their chemical compositions. A stocktake of the matte, slag and concentrate stockpiles was conducted annually to determine the accumulation or depletion of stock on the sites and to assess the grades of the stockpiles.

Calculation of Recoveries of Base Metals

Assays of the concentrate (*c*), matte (*m*) and slag (*s*) were provided. These assays reported the various base metal contents (%) within each of these materials. The percentage recovery (*R*), upgrade ratio (*UR*) and percentage matte fall (ratio of the amount of product (matte) formed as a percentage of the amount of feed to the furnace) were calculated from the assays (Equations [3] to [5]). This was performed through a standard mass balance derivation two-product recovery formula and will hereafter be called site recoveries.

$$R\ (\%) = \frac{100m(c-s)}{c(m-s)} \qquad [3]$$

$$UR = \frac{m}{c} \qquad [4]$$

$$Matte\ Fall\ (\%) = \frac{100(c-s)}{(m-s)} \qquad [5]$$

Equations [3] to [5] form the basis of the modelling. The approach utilised the base metal content as the independent variable. The initial data was obtained in Excel spreadsheets and had to undergo some refinement to ensure that the data in the model was consistent. In order to do so, the following steps were taken:

- All data had to have corresponding matte, slag and concentrate values
- All data from months with shutdowns was discarded

The resultant data was then exported to MATLAB, where the model regression analysis was applied. This was done by minimising an error formula, determining the differences between different values of the coefficients. The solution is the minimum of these differences.

Based on the compositional assay data, the recovery of the individual base metal elements was determined. To determine the effect of the base metal content on these individual element recoveries, the recoveries and upgrade ratios were plotted against the base metal compositions of the feed. Based on the shape of the curve observed in the experimental data, it was decided to model the data according to a n–th order curve in the form of:

$$z = \left(\frac{B}{x^C}\right) + D \qquad [6]$$

where z is the recovery of the metal, x is the composition of the base metals in the concentrate and B, C and D are constants that are determined through the regression analysis. A similar approach was applied for the modelling of the base metal upgrade ratios. This will hereafter be termed the data model.

Regression analysis

The constants B, C and D in the model are determined through minimisation of the calculated difference between the modelled and measured data points. The error was calculated using the sum squared error. The choice was due to the fact that sum of squares error (*SSE*) is calculated through the difference of the measured value and the modelled value. The formula for *SSE* is given by:

$$Sum\ Squared\ Error\ (SSE) = \sum_{i=0}^{n} \left(Recovery_{measured_i} - Recovery_{modelled_i}\right)^2 \qquad [7]$$

- $Recovery_{measured,i}$ i_{th} value of the variable modelled
- $Recovery_{modelled,\ i}$ modelled value

The error was subsequently minimised using the *fminsearch* function on MATLAB. The *fminsearch* function is used to find the minimum of a scalar function (using an initial estimate). The purpose is to search for the values of constants *B*, *C* and *D* in the model to minimize the error between the modelled data and the experimental data. The arguments applied to *fminsearch* were as follows. The SSE function is the function to be minimised. It accepts an input *x* (*SSE* at point *x*) and returns a scalar f, the objective function minimised at *x*. The function can be specified as a function handle.

x = fminsearch(@SSE,x0,B,C,D) [8]

Data Model validation

Upon development of the model, the statistical method employed to determine the goodness of fit was the Kolmogorov-Smirnov test. Assuming an $\alpha = 0.05$, this allows the test to determine whether there is a statistical difference between the modelled values and the measured values. The kstest function on

MATLAB is used to compare the empirical cumulative distribution functions (CDFs) of the data set with the CDF of the model data. The resultant models were then further tested against a test set of data to determine any statistical difference between the model and the test data. According to the statistical analysis, the null hypothesis could not be rejected and this showed no statistical difference between the modelled data and the test data. A total of 193 data points was used with a p-values of less than 0.1 determined.

RESULTS

Recovery and upgrade ratio models

Theoretically, based on the iron content of the matte and slag, the calculation of recovery of the non-ferrous metals from equation [3] showed that the base metal (Ni, Cu and Co) recovery does indeed increase with the lower recovery of iron to the slag phase, as indicated in Figure 2.

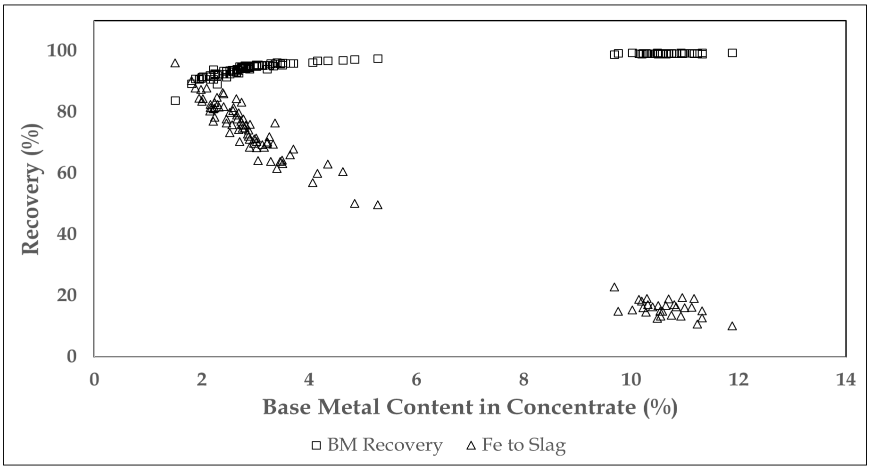

Figure 2. Non-ferrous base metal recovery to the matte and iron recovery to the slag as a function of total base metal content in the concentrate.

There is a correlation between the recovery of cobalt, nickel and copper and the amount of iron that reports to slag based on the amount of iron and base metal sulfides present in the feed. Equations [1] and [2] for Grimsey's model were plotted against the two-product site recovery values (Equation [3]) in Figure 3. The average K'_{Me} values were calculated for each of the metals. The presence of higher base metal and iron sulfides contents leads to a greater amount of matte forming, and less iron reporting to slag. Where base metal oxides are present in the primary furnace, higher iron sulfide contents may allow for reduction of the base metal oxides to their more stable sulfides, and also contribute to a greater recovery of iron to matte. While there is good agreement with Grimsey's model at lower iron recovery to slag, the site recoveries statistically deviated from Grimsey's model at higher recoveries of iron to slag for an average K'_{Me} value for the entire dataset.

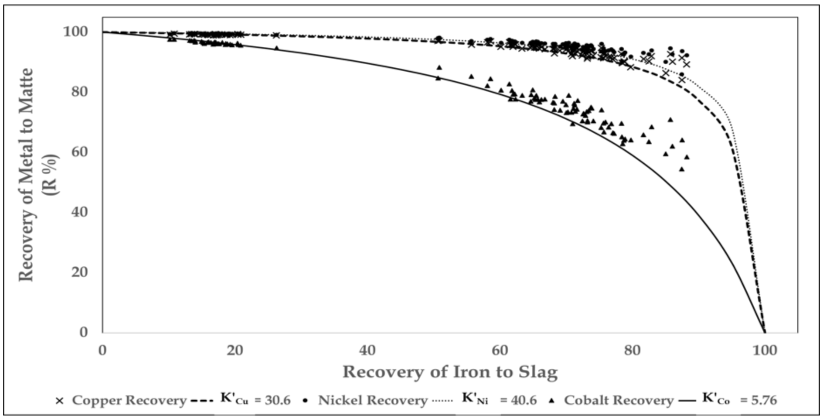

Figure 3. Grimsey model and site cobalt, copper and nickel recoveries as a function of recovery of iron to slag.

K'_{Me} values were calculated at different ranges in the dataset, which showed significant differences between the Grimsey model and the site recoveries, as a means to test whether different operating conditions in the different smelters could be a contributing factor (Table I). It further emphasised that even when the K'_{Me} values were calculated within a specific range, differences in recoveries predicted and the site recoveries exist. As a result, an additional data-based model was proposed and developed.

Table I. Average K'_{Me} values for the base metals in different ranges of iron reporting to slag and the resultant difference in recovery between the Grimsey model recovery and site recovery

Iron to Slag (%)	K'_{Me}			Difference in Site Recovery & Grimsey Model Recovery (%)		
	K'_{Co}	K'_{Ni}	K'_{Cu}	Co	Ni	Cu
0 - 15	5.60	40.33	30.7	-0.223	-0.017	-0.089
15 - 60	5.50	42.6	32.2	0.353	0.087	0.035
60 - 80	5.95	44.1	32.4	3.173	0.707	0.835
80 - 100	5.90	40.9	31	12.9	5.02	5.88

Data recovery models and upgrade ratio models were determined using regression analyses through the use of MATLAB and minimising the differences between the model and the recorded data using the sum of squared errors. The independent variables for the base metal models of recovery and upgrade ratios were the respective base metal compositions in the concentrate. The use of base metal concentration (%) was also used as a proxy for the iron in the feed (%) (Figure 4).

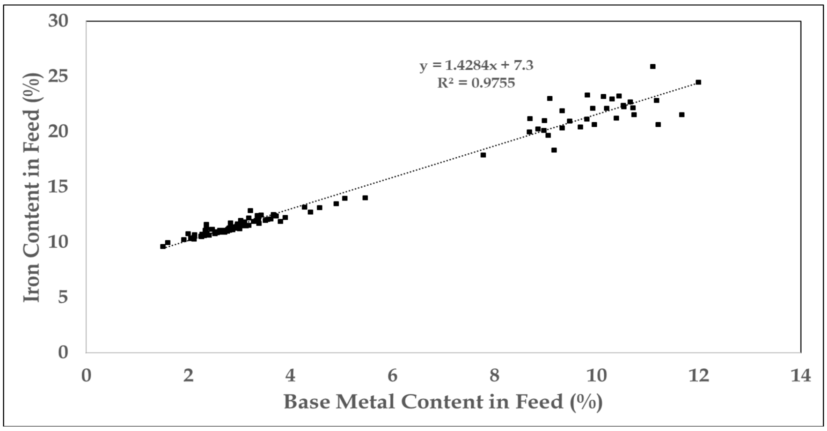

Figure 4. Relationship between iron content in the feed to base metal content.

The base metal recovery and upgrade ratio based on the site data as well as the data models are shown in Figures 5 and 6. The figures indicate that the model can be used to represent the base metal recovery profiles of all smelters, despite their differing feed compositions, feed blends, power inputs and furnace shapes and dimensions. Based on the shape of the curve witnessed in the experimental data, it was decided to similarly model the data according to an n-th order curve (Equation [6]).

The resultant recovery and upgrade ratio models for base metals was modelled with the following parameters:

Table II. Modelled parameters for the base metal recovery and upgrade ratio data models as a function of base metals in the concentrate (with Ni/Cu ratios varying from 1.1 to 2)

Data Model	Model Equation	*B*	*C*	*D*	*SSE*
Co Recovery Model	$Co\ Recovery\ \% = \left(\frac{B}{(Co\ Conc\ (\%))^{C}}\right) + D$	-0.903	1.18	105	894
Co UR Model	$Co\ UR = \left(\frac{B}{(Co\ Conc\ (\%))^{C}}\right) + D$	0.312	1.02	0.177	17.4
Cu Recovery Model	$Cu\ Recovery\ \% = \left(\frac{B}{(Cu\ Conc\ (\%))^{C}}\right) + D$	-7.01	1.21	100	112
Cu UR Model	$Cu\ UR = \left(\frac{B}{(Cu\ Conc\ (\%))^{C}}\right) + D$	9.31	1.08	-0.314	34.2
Ni Recovery Model	$Ni\ Recovery\ \% = \left(\frac{B}{(Ni\ Conc\ (\%))^{C}}\right) + D$	-10.4	1.37	101	99.4
Ni UR Model	$Ni\ UR = \left(\frac{B}{(Ni\ Conc\ (\%))^{C}}\right) + D$	15.1	1.06	0.314	34.2

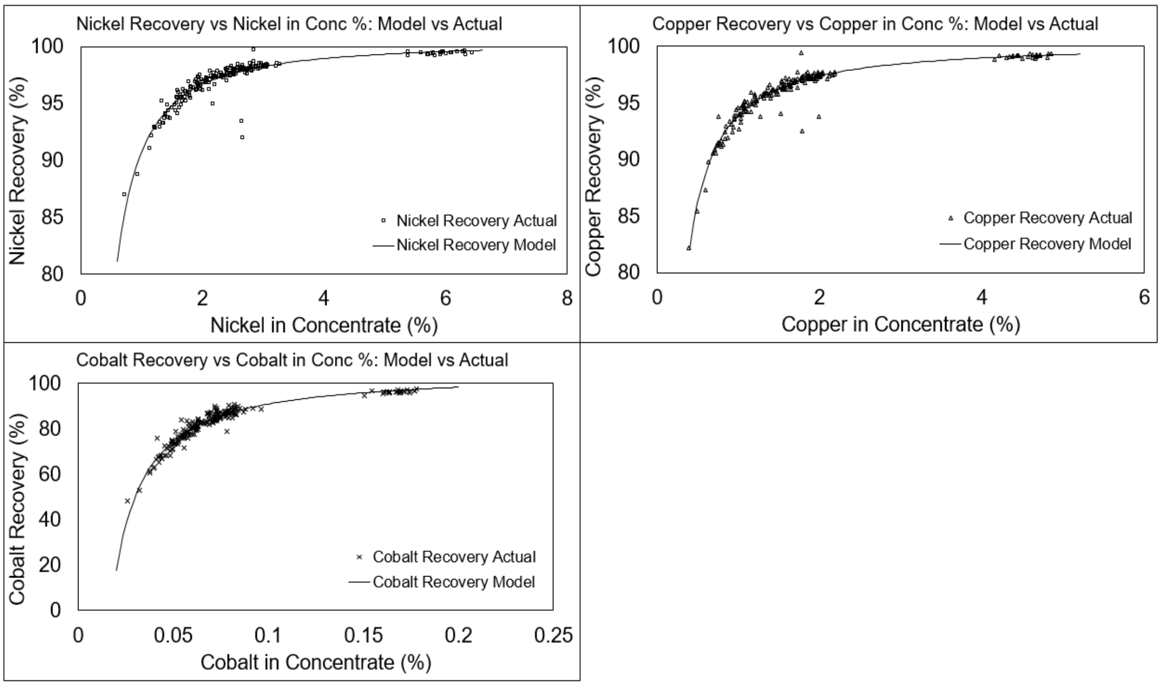

Figure 5. Data recovery models vs site base metal recoveries as a function of base metal content in the concentrate.

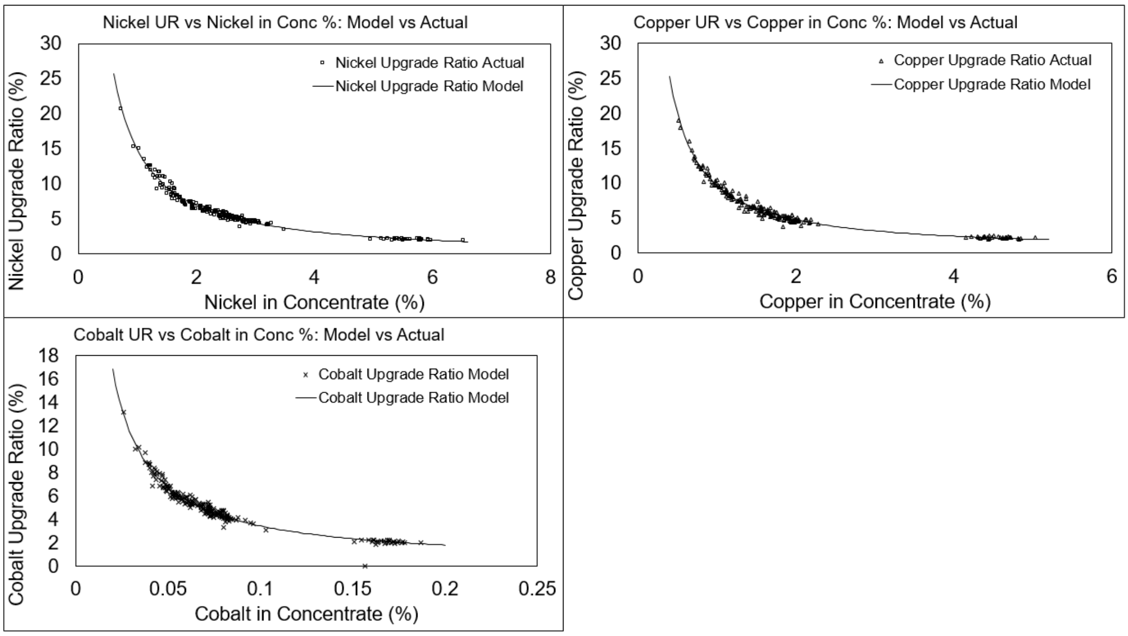

Figure 6. Data upgrade ratio models vs site base metal upgrade ratios as a function of base metal content in the concentrate.

In an effort to include the mitigating effects, a data-driven regression model was developed for recoveries and upgrade ratios based on the feed composition entering the smelter. This was accomplished for the base metals (copper, nickel and cobalt). Based on the formula for an nth-order relationship, the constants for the model for each of the recoveries and upgrade ratios were determined through regression analysis in MATLAB and the error minimised through the use of *SSE*. Using the *fminsearch* function, the model converged successfully. Doing statistical analyses of the model in comparison to a test set of data, the models were determined to not have any statistical difference to the test data.

Through the use of the models to determine the base metal recovery and the grades of base metals in the matte, a calculation can be made to determine the throughput of base metals based on the furnace feed rate and the maintenance regime of the operations. Based on these factors, the amount of base metals formed per MWh can be determined.

Matte Fall Model

The matte fall is calculated as the mass fraction of the feed (concentrate) reporting to the product phase (matte), expressed in percentage (Equation 5).

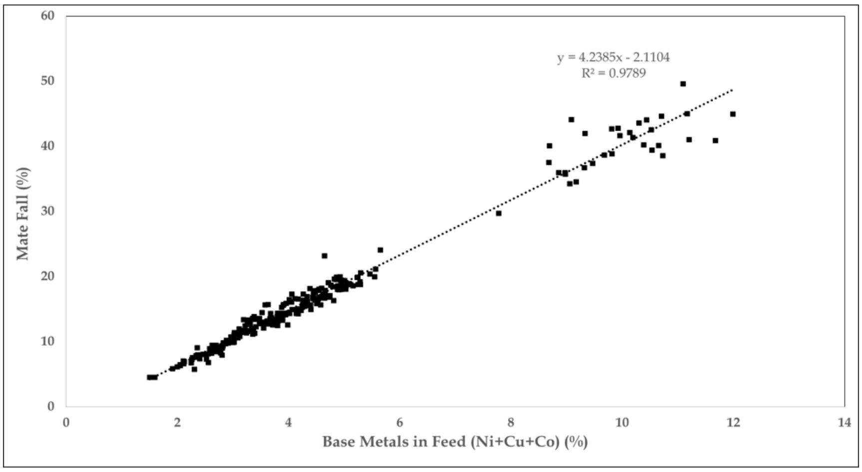

Figure 7. Matte fall vs base metal content in feed.

The development of a matte fall model indicates a linear trend for the three operational sites in question and the use thereof can ultimately influence the ability of metallurgists and engineers on the operational sites to plan accordingly to deal with the amount of matte phase tapped. More scatter at higher base metal contents was noticed for the Unki data points where corrections were made for the silica sand pits addition and lime addition, assuming a constant content of silica and lime respectively.

Calculation of Matte Production

Ultimately, to ensure sustainability of an operational site, the amount of valuable metals that are upgraded through smelting needs to be optimised. This must be done in the context of obtaining as high a recovery as possible within the confines of a grade profile that is still acceptable to downstream processing. As a result of the data recovery and matte fall models, it is possible to predict the amount of matte to be tapped, along with its composition, based on the composition of the concentrate fed.

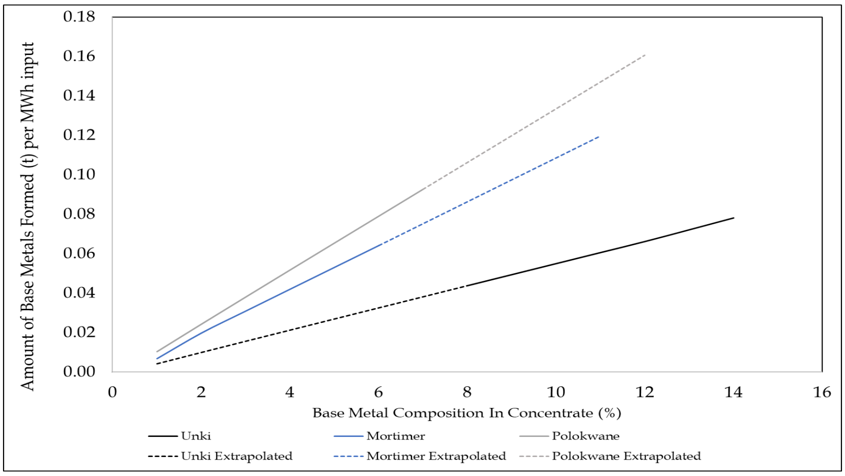

Figure 8. Matte fall vs base metal % in feed.

At lower base metal compositions in the feed, the three different furnaces are more aligned in the amount of base metals in matte per MWh input into the furnace. At higher base metal concentrations however, the operational sites start to diverge. These can be changed by influencing the ability to remove matte more effectively from the furnace or through changing maintenance profiles accordingly.

DISCUSSION

The matte, slag and concentrate composition data of the Mortimer, Polokwane and Unki operations allowed for the calculation of the recovery of the base metals and precious metals across three furnace operations of Anglo American Platinum. The sampled data was obtained from the individual sites, which measure the composition of the concentrate inputs, as well as the matte and slag outputs through a sophisticated sampling regime.

The Grimsey model for base metal recovery compared well with the site recoveries when less than 60% of the iron from the concentrate reported to the slag phase. At values greater than 60%, the Grimsey model and site base metal recoveries began to deviate. When more than 60% of the iron reports to slag, the average difference between the model and the experimental data recoveries were approximately 3%, and the difference was up to 25% when most of the iron reported to slag. When less than 60% of the iron reports to the slag, the average difference between the modelled recovery and the experimental data was 0.04%.

The average values for the K'_{Co}, K'_{Ni} and K'_{Cu} for the non-reducing PGM furnaces considered in this analysis were 5.76, 40.6 and 30.6 respectively. Comparatively, in a flash smelting study, values for K'_{Co}, K'_{Ni} and K'_{Cu} were 11, 270 and 66 respectively, at much more reducing conditions (Grimsey, 1993).

Grimsey, 2021 indicated that the model (Equation [1]) did not include the influences of matte entrainment. In the PGM smelting furnaces matte entrainment could be present due to the influence of chromite in concentrate giving rise to spinel layers entrapping matte droplets. This would be more characteristic of high UG2 content concentrates with lower base metal feed contents, however since the site recoveries are noted to be higher, it is deemed that entrainment does not affect the result. Oxidic base metals losses will occur at different levels of slag oxidation state (using iron in slag as a proxy) with cobalt being the first to be lost and thereafter nickel and copper. It is postulated that the higher site recoveries relative to the model may be partially explained through reducing conditions (with a pO_2 between 10^{-9} bar and 10^{-8} bar at temperatures between 1550°C to 1600°C in the slag (Nell, 2004)) within the furnaces, including the presence of carbon from electrode consumption, and the reduction in the localised region of the electrodes. This could result in some of the of the oxidised base metals being reduced with the formation of CO. FeS itself can act as a reductant for the oxidised base metals. Approximately, 41.3 tonnes of carbon is added to the furnace on average per month in the form of paste via the electrode wear at the low base metal content feeds which is in the order of magnitude required to account for the difference between the site recovery and Grimsey's recoveries.

The utilisation of a data-driven model, using regression analysis helps consider these impacts and was applied to the different furnaces which operate at different powers and feed compositions to provide for a wide range of data points that allow for validity and confidence in the model.

Utilising the matte fall, upgrade ratio and recovery data models, there is an opportunity to optimise base metal throughput and the PGMs associated with the base metals by understanding the feed compositions to the furnace. Changing the maintenance regimes and the design capacities of the feeding and tapping arrangements may help improve the resultant base metal throughput per MWh (Figure 8) to align; however this may result in capital expenditure. If the current status quo is maintained, it may be well to ensure that the lower base metal feed content is directed to the smaller furnaces where possible, to ensure the maximisation of base metals produced for a given electrical input within the bounds of not exceeding Cr_2O_3 limits, matte production limits and other techno-economic cost factors.

CONCLUSIONS

The concentrate utilised within the PGM industry plays a significant role in how the process is designed and governed and influences the products formed, namely matte and slag. The properties of the concentrates ultimately drive the properties of these products and subsequently impact the recovery of the valuable base metals and PGMs. To ensure sufficient recovery of valuable metals, the conditions within the furnace need to be adjusted, depending on the type of feed.

The variations in the concentrate base metal composition have been shown to be a primary driver in the recovery of the base metals (and associated PGMs) in the product. The ability to develop a recovery curve (Figure 5) based on the changes in feed base metal content allows for greater understanding of the smelting process and the planning thereof. Although the Grimsey model fits the site recovery data well in a portion of the data, other portions were not well represented.

The models developed can be utilised for strategic planning of the operations for the range of compositions available. The composition of the concentrate, as a function of the ore being mined, can be used to formulate and predict the recovery and amount of valuable metals, and can be used to develop operating strategies in the smelters themselves to maximise both recovery and grades, depending on the downstream and market requirements. This could be achieved by ensuring that the reduction of the base metals is maximised which was postulated to be the largest inhibitor to base metal losses.

An opportunity exists, depending on the amount of concentrate made available to the furnaces from the different UG2 and Platreef concentrators, to blend the concentrates to optimise for recoveries. In feed-constrained conditions, this is not possible but the models could serve as a prediction of the opportunity presented when feeding a consistent and stable blend and the possible opportunities from a stable and capable process. An example could be various periods requiring high availability or high concentrate stocks or in periods where the cost of running the furnace may be inherently cheaper, such as the summer months. In the winter months it may be prudent to increase the base metal content in the feed to result in the same outputs at a lower operational cost due to a higher amount of downtime. Since PGMs are the primary driver of the revenue of the business, it is prudent to ensure that the PGM's grades associated with the base metals can be further optimised inferred by the base metal content to drive the PGM throughput through the smelting regime.

REFERENCES

Anglo American plc (2021), Ore Reserves and Mineral Resources Report 2021, 1 - 57

Eksteen, J.J., van Beek, B. and Bezuidenhout, G.A. (2011). *Cracking a hard nut: An overview of Lonmin's operations directed at smelting UG2-rich concentrate blends*, The Journal of the South African Institute of Mining and Metallurgy, vol. 111, 681 – 690.

Engelbrecht, J. U. (2012). Potential Changes in the Physical Beneficiation Processes That Can Improve the Recovery Grade or Costs for the Platinum Group Metals. Proceedings of the Fifth International Platinum Conference: A Catalyst for Change. The Southern African Institute of Mining and Metallurgy. Sun City, South Africa.

Eric, R.H. (2004). *Slag properties and design issues pertinent to matte smelting electric furnaces*, The Journal of The South African Institute of Mining and Metallurgy, October 2004, 499 – 510.

Georgalli, G.A. and Anderson, D.K. (2010). *Optimizing concentrate allocation to Anglo Platinum smelters*, The 4th International Platinum Conference, Platinum in transition 'Boom or Bust', The Southern African Institute of Mining and Metallurgy.

Grimsey, E.J. (1993). *Metal Recovery in Nickel Smelting and Converting Operations*, The Paul E. Queneau International Symposium, Extractive Metallurgy of Copper, Nickel and Cobalt, Volume I: Fundamental Aspects, 1239 - 1251

Grimsey, E.J. (2021). *A Comparison of Two Novel Non-Ferrous Metal Recovery Equations: Development, Similarity and Industrial Significance*, Metallurgical And Materials Transactions B, July 2021

Gunn, G. and Benham, A. (2009). *British geological survey – Platinum, Natural Environment Research Council*, 1 – 31.

Hundermark, R.J., Mncwango, S.B., de Villiers, L.P.vS. and Nelson, L.R. (2011). *The smelting operations of Anglo American's platinum business: an update*, Proceedings of Southern African Pyrometallurgy 2011, Johannesburg, 6 – 9 March 2011, 295 – 308.

Ip, S.W., Toguri, J.M. *Entrainment behavior of copper and copper matte in copper smelting operations*, Metallurgical Transactions B 23, 303–311

Jones, R.T., Geldenhuys, I.J. and Reynolds, Q.G. (2009). *Recovery of base metals and PGMs in a DC alloy-smelting furnace*. Journal of the Southern African Institute of Mining and Metallurgy, 109(10), 595-600

Mkhize, B. and Andrews, L. (2011). *Smelter feed quality control*, Minerals Engineering, Volume 24, Issue 12, Pages 1365-1369,

O'Connor, C. and Alexandrova, T. (2021). *The Geological Occurrence, Mineralogy, and Processing by Flotation of Platinum Group Minerals (PGMs) in South Africa and Russia*, Minerals 11

Oberthür, T. (2011). *Platinum-Group Element Mineralization of the Main Sulfide Zone, Great Dyke, Zimbabwe,* Magmatic Ni-Cu and PGE Deposits: Geology, Geochemistry, and Genesis, Chusi Li, Edward M. Ripley

Oberthür, T., Melcher, F., Buchholz, P. and Locmelis, M. (2013). *The oxidized ores of the main sulphide zone, Great Dyke, Zimbabwe: turning resources into minable reserves–mineralogy is the key*, The Journal of The Southern African Institute of Mining and Metallurgy, vol. 11, 191 – 220.

Nagaraj, D.R. (2005) *Minerals Recovery and Processing*. Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, Inc., Hoboken, 2-10

Nell, J. (2004). *Melting of platinum group metal concentrates in South Africa*, The Journal of the South African Institute of Mining and Metallurgy, vol. 104, no. 9. 423–428.

Nelson, L.R., Georgalli, G.A. Hines, K.L., Hundermark, R.J. (2018), Converter processing of platinum group metals, Mineral Processing and Extractive Metallurgy, Volume 128, Issue 1-2 134-159

Rivera Li Kao, O. and Garbers-Craig, A.M. (2022). *Impact of Phase Evolution in Platreef and UG-2 Concentrates on Matte Drainage in the Black Top of a Platinum Group Metal Smelter*, Mineral Processing and Extractive Metallurgy Review, 43:3, 326-338

Waldner, P. and Pelton, A. D. (2005). *Thermodynamic Modeling of the Fe-S System*. Journal of Phase Equilibria and Diffusion, 26, 23-38.

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